THE EFFICIENT HOUSE INNOVATION

HEALTHFUL, EFFICIENT AND SUSTAINABLE HOUSING FOR NORTHERN AND SOUTHERN CLIMATES

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This publication may be cited as:
Gillies, T. & Poulin, T. (2015). The efficient house innovation: Healthful, efficient and sustainable housing for northern and southern climates. In M. Panko and L. Kestle (Eds.). ***Building Today - Saving Tomorrow: Sustainability In Construction And Deconstruction Conference Proceedings***. (pp. 44-57). Auckland, New Zealand: Unitec Institute of Technology. Retrieved from: www.unitec.ac.nz/epress/

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ISBN 978-1-927214-17-6

ABSTRACT

This paper tracks the Efficient House Innovation (EHI) from 2000 to 2015. The main idea of 'Dynamic Air' behind EHI is associated with John Timusk (1987) who recognised existing housing solutions were not sufficiently healthful, efficient or robust. His solution was to bring relatively cool, dry air dynamically through the walls instead of the usual air-tight, static construction. However some problems remained. Starting in 2000, the authors of this paper extended and added features to Timusk's solution to arrive at the EHI. Initial tests of EHI prototypes indicate the reliable fresh air, robustness of structure and energy efficiency that Timusk envisioned. This paper focuses on EHI prototype testing from 2008 to 2015, with implications for housing in cold, temperate and sub-tropical climates.

INTRODUCTION

It has been reported that buildings in general use about 40% of total energy and more than 50% of all energy worldwide, if embodied energy during construction and deconstruction of failed solutions are taken into account (Cigler, Tomosko & Siroky, 2013; Todorovic & Kim, 2012). Housing consumes more than half of buildings and about 30% of worldwide energy, much of this inefficiently.

Inefficient energy use is one issue. Another is that air quality and durability of housing are too often compromised within the first few years of construction. This leads to the conclusion that improving air quality and structural robustness is as important as energy use (U.S. EIA, 2012, 2014; and Ontario Clean Air Alliance, 2011). This is particularly true in far Northern and far Southern climates where people face extreme winters in houses offering insufficient efficiency, poor air quality and compromised durability. The Efficient House Innovation (EHI) is one promising solution.

For centuries traditional houses may have had their faults in terms of energy efficiency but these did not rot or introduce mould like houses in much of the world today. Out of this realisation the "dynamic air" concept was born (Timusk, 1987). As with earlier variations of the idea, the EHI draws outside air through the exterior of a house, to supply fresh air, and improve energy efficiency and longevity of the structure of houses (Chow et al. 2010; Rosart et al. 2014). A major aspect of the EHI is conceptually shown in Figure 1.

Figure 1 illustrates how conductive heat loss can be recovered; this aspect is ignored by building codes that only handle convective, not other heat losses or gains with mostly fibre insulation. The other two mechanisms of heat transfer, conduction and radiation, are either addressed partially or not at all. Similarly, air quality and structural robustness are either ignored or inadequately handled by building practices and codes. For example codes and standard building practices ignore drying of interstitial, within-wall, moisture that can lead to mould and rot in wood structures.

The EHI is a science and engineering-based concept designed to improve all aspects of performance of houses, for all climates except tropical: health, efficiency and structure. It is based on the realisation that current building codes and practices of sealing up our houses need to be re-examined; the starting point is to look to the early dynamic air approach of scientist John Timusk (1987).

Note: An early and partial version of the research reported here was presented to a management and technology conference in 2012, Ryerson University, Canada. This paper reports on both this previous and also on new research and development work in 2014 and 2015. As an aside, the authors also regularly visit Australasia and particularly New Zealand, both professionally and personally to visit colleagues, families and friends.

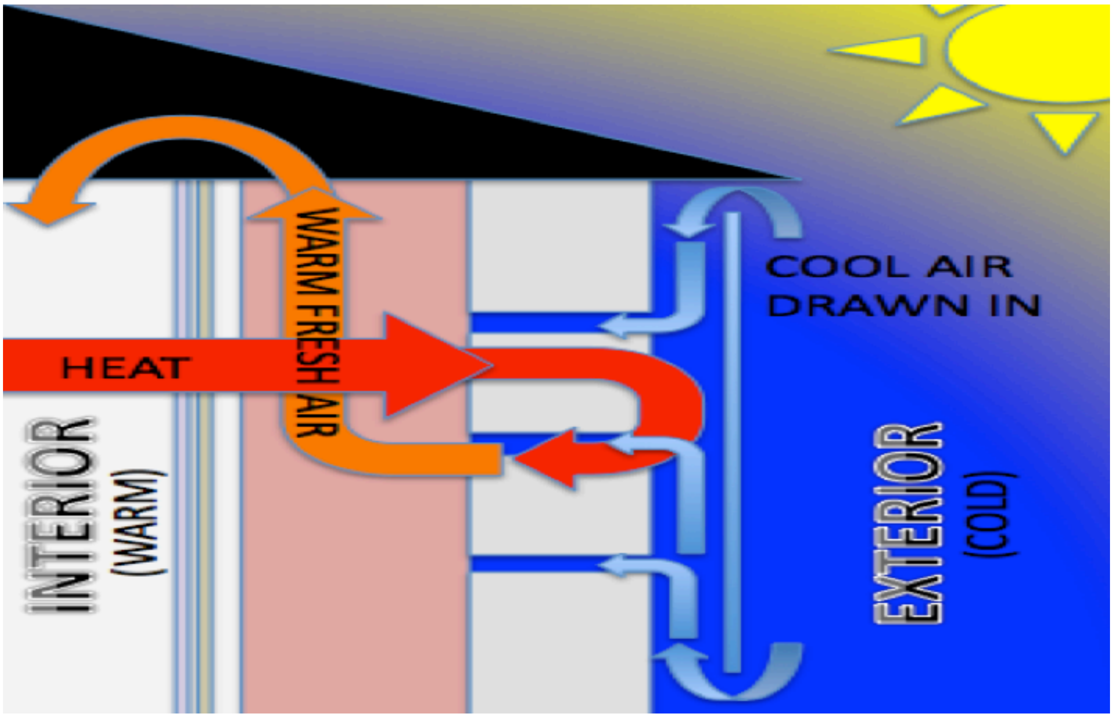

Figure 1: Dynamic Heat Transfer in exterior walls
Source: Authors own and as adapted from ideas contained in Timusk (1987).

Timusk's Dynamic Wall Approach: Forerunner to EHI

The Dynamic (or breathing) Wall (DW) approach to housing in Canada is associated with John Timusk (1987), formerly head of the Centre for Building Science at the University of Toronto, Canada. In late 1970 Timusk recognised the need to improve energy efficiency, durability and fresh air supply in housing. He and a colleague in Sweden were concerned about the plastic bubble method being used to save energy in housing (Timusk 1987). This involved stuffing ever-more insulation between the framing of exterior-facing walls and ceilings, together with sealing up the envelope in ways that could trap moisture; the latter causing extensive problems, including mouldy exterior walls and unlivable conditions: sometimes referred to as sick house syndrome

Going back to basic physics, Timusk came up with a new approach for housing that turned the plastic bubble approach on its head by addressing both convection and conduction in a way so as to provide fresh air to occupants while also keeping the structure dry. His concept showed promise, though early application was flawed. For example, when the houses were depressurised to bring in the fresh air, unanticipated air was drawn through gaps around exterior doors and windows. Timusk's dynamic wall approach needed improvement.

UNDERSTANDING, IMPROVING AND EXTENDING THE DYNAMIC WALL APPROACH

As indicated, the idea of Timusk's dynamic wall approach was to slowly draw relatively cooler and drier fresh air through the exterior walls from the outside to recover conductive heat, dry exterior-facing walls, and supply fresh air to occupants. Calculations made on the basis of standard heat flow science and air permeability characteristics of common building materials suggested that both fresh air supply and heat recovery in winter conditions were possible. The following are equations for calculating heat loss or gains, by conduction, radiation and convection (for example, Timusk, 1987, p.63).

Conductive heat loss rate – in the direction of decreasing temperature:

Where:

$$Q = \frac{A\ \Delta T}{RSI} \qquad Equation\ 2.1$$

Q	Heat transfer per unit time (Watts)
A	Surface area (m^2)
ΔT	Temperature difference across the material (˚C or K)
RSI	Thermal resistance of the material (m^2 C/W)

The principle step in conductive heat loss reduction is to specify materials with adequate thermal resistance across the envelope.

Radiant heat loss rate – transfer of heat through electromagnetic radiation:

Where:

$$Q = \varepsilon\sigma A(T_s^4 - T_a^4) \qquad Equation\ 2.2$$

Q	Heat transfer per unit time (Watts)
$\mathcal{E}\delta$	Thermal emittance, emissivity as a fraction of a perfect black body (1) versus perfectly reflective surface (0). Many natural building materials have an emissivity of about 0.9
T_s	Surface temperature (˚C or K)
T_a	Outdoor surface temperature (˚C or K), usually taken as the ambient air temperature

Radiant heat loss can be reduced by incorporating a reflective barrier and adjacent air space in the envelope, but this is not common practice. Also the importance of maintaining the air space is not recognised in many installations.

Convective heat loss – energy transfer between a solid surface at one temperature and an adjacent moving gas (air) at another temperature – can be modelled as follows:

Where:

$$Q = h_c A(T_s - T_\infty) \qquad Equation\ 2.3$$

Q	Heat transfer per unit time (Watts)
h_c	Convective heat transfer coefficient (W/m^2 K). Values range from 5-25 for naturally convecting air to 25-250 for forced air convection.
A	Surface area (m^2)
T_s	Temperature of the surface (˚C or K)
$T\infty$	Temperature of the air at a distance far enough not to be affected by the surface temperature

Convective heat loss is lessened by filling stud cavities with a material of low thermal conductivity but sufficient mass to limit natural convective air current loops (e.g. fiberglass batts). Convective heat loss also occurs through envelope leakage paths.

The concept of the Dynamic Wall Approach was to address convective and conductive heat loss and gain and, at the same time provide a means for supplying fresh air to occupants while controlling for mould and structural robustness. All this is theoretically possible by simply drawing relatively dry air through the exterior envelope. The optimum flow rate of the air flowing through a dynamic wall or roof system is that at which all the conductive heat within the insulation layer is transferred to the incoming ventilation air. By equating the conductive heat loss rate through the still air in the insulation layer (Equation 2.4) to the rate that air is able to absorb heat (equation 2.5), the optimum rate of air flow, q, through the dynamic envelope component (wall, ceiling or floor), can be determined (Equation 2.6) (Timusk, 1987, p.63).

Where

$$Q = \left(\frac{k}{t}\right) A\, \Delta T \qquad Equation\ 2.4$$

Q	Conductive heat loss through the air in the insulation (W)
k	Coefficient of thermal conductivity of air (0.025 W/m K)
t	Thickness of insulation layer (m)
ΔT	Difference in temperature across the insulation layer (°C or K)

And

Where

$$Q = q\, \rho\, c_p\, \Delta T \qquad Equation\ 2.5$$

Q	Rate of heat absorption by the incoming air (W)
q	Rate of air flow through the envelope component, m^3/s
p	Specific density of air (kg/m^3)
C_p	Specific Heat of Air, (J/kg)
ΔT	Temperature difference across the layer (°C or K)

Resulting in the optimum airflow, q (m/s):

$$q = \left(\frac{k}{\rho\, c_p}\right)\left(\frac{A}{t}\right) \qquad Equation\ 2.6$$

Dynamic Wall Performance and Potential

The early dynamic air houses constructed under Timusk’s direction in Alberta did result in good air quality but fell short of predicted heat recovery gains, at about half that predicted. The disappointing heat recovery result was due to unanticipated and uncontrolled air infiltration (Mayhew, 1987; Nakatsui, 1996). As Timusk (1987) reported, the Swedish Building Council also found its similarly dynamic Swedish houses enjoyed mixed results: reasonably good indoor air quality but energy goals not met.

Despite these limitations, the concept of dynamic air showed promise. With new and complementary ideas, the potential may have been possible in the 1990s. However, it would be another decade before a complete system using dynamic air was invented. This lack of interest in further development was partly due to low energy prices at the time and the missing elements to the innovation and the process (DeProphetis, 2006).

RESEARCH METHODS

Timusk (personal conversation, 1999) later recognised his failure in two modes: not sufficiently improving on his idea; and not setting in place sufficient social and commercialisation opportunities. The authors of this paper, one an engineering professor and the other a business professor with an engineering background, set out to avoid the failure modes while building on Timusk’s early concept of dynamic air. The enhanced innovation involved three main steps:

1. Technology extension by improved design (e.g. drawing fresh air from exterior walls and ceiling areas, and adding a radiant material in the walls);
2. Prototype testing; and
3. Management of the innovation process.

Re-examination of heat loss and the innovation process itself were first steps, since these were likely where more attention was needed. Under guided supervision, two graduate students set about initial re-examinations, with the following general results.

1. It is established that innovation can lead to creative destruction as the old is replaced by the new, sometimes a very difficult process (Schumpeter, 1942, pp. 82–83).
2. Innovation is a combination of science and engineering insight and advances as well as management of the innovation process from idea to feasibility to commercial reality (Burgleman, 1984; Poulin, 1987).
3. Although innovation tends to destroy inferior systems, the journey can be fraught with difficulty as existing industry and culture resist change.

In this case, overlooked aspects of the science, constraining building codes, entrenched industry practices and weaknesses in the innovation process would all have to be identified and overcome.

The Innovation Process

Burgleman (1984) classified the innovation process in terms of three levels or stages, where decision-makers need to be successful at each level. Table 1. summarises the innovation and new venture process at each of three stages and levels.

Stage	Key Decision Makers	Process & Outcomes	Strategy, Resources & Structure
Stage 1: **Idea/ Concept**	Project managers selected for ability to act as innovation champions	Engineering and management are integrated	Strategy outlined, resources given, flexible structure established
Stage 2: **Feasibility/Prototype testing**	Mid-level corporate managers chosen for their engineering and management knowledge and experience	Scarce resources secured as warranted to develop and test prototypes for feasibility	Substantial collaboration between engineers, mid-level managers and senior-level managers
Stage 3: **Commercialization**	Very senior level corporate managers enlisted to both fairly evaluate and support the new venture	Innovation and venture are fairly evaluated (all this assumes competent senior managers)	Corporate support for new venture with continuous learning among mid-level and top level managers

Table 1. Process of Innovation and New Venture
Source: adapted from Burgelman (1984) and Poulin (1987)

From examination of the innovation process, it is apparent that by the end of the 1980s the Dynamic Wall Approach was failing in some of the key elements required for success. For example, the idea was stuck between Stage 1 and Stage 2, due to limitations in resources that might have led to further refinement of the idea. It was no surprise, looking back, that the project managers would go on to other things.

Resetting the stage for the dynamic wall to become a successful innovation required a combination of better science and engineering design, prototype development and management of the innovation process. Two of the first steps were to examine limitations of building codes and practices, and to look closely to see if Timusk had missed something important with his Dynamic Wall Approach.

Failure of Building Practices and Codes to Account for Science

The three mechanisms of heat loss and gain are not sufficiency dealt with in typical building codes. Convection (e.g. air currents that transfer heat from warm to cold) is controlled by code regulation and this is accomplished by builders installing fibre insulation between studs of the exterior walls and ceiling joists/trusses. Conduction is inadequately handled by building practices by installing rigid insulation to slowing down conductive heat transfer. Radiation is ignored by building codes and practices.

Extending the Dynamic Wall Approach of 1980s in the 2000s

In 1998, one of the early advocates of Timusk's technology returned from 10 years of academic service in New Zealand, accepting a faculty position at Lakehead University in Canada. In 1999 he contacted Dr. John Timusk and found nothing had been done on the Dynamic Air Approach since the Edmonton houses of the 1980s (Timusk, personal conversation, 1999).

Timusk made a suggestion for improving the system (contained in a letter dated February 2, 1999) where he recommends depressurising the exterior walls rather than the entire house. This is to overcome the problem of unanticipated infiltration air, a partial explanation for the heat recovery being less than predicted by his design calculations. Later it became apparent that Timusk omitted to address radiant heat losses in his theory and the building of early houses he demonstrated in Ontario and Alberta. This provided added reason for the lower than expected heating efficacy.

Based on the above, including the results of the student studies, the two professors at Lakehead University (both civil engineers, one teaching engineering and the other teaching business) agreed to work at extending Timusk's previous work. The one focused on engineering with his engineering students while the other focused on innovation with business students, each suggesting ideas to improve the others' work.

Also by the 2000s, oil prices had risen. This caught the attention of funding agencies, helping the research team obtain seed funding for research and prototype development and testing. A parallel effort existed in Europe.

The two centres were University of Aberdeen, Scotland and Lakehead University, Canada. The approach by both Aberdeen and Lakehead was to depressurise the exterior walls, as distinguished from Timusk's earlier Dynamic Air Approach where he depressurised the entire house.

While outwardly similar, the two University-based initiatives differed considerably. For example the Aberdeen group focused on inventing proprietary and prefabricated exterior wall panels that would allow air to pass through the exterior walls, while the Lakehead group focused on understanding the physics and mechanisms of heat gain and loss, and optimising the entire system using existing building materials and construction methods.

Research Aims of the Efficient House Innovation

The research aims came about from initial studies conducted from 1999 to 2004 by the two authors of this paper and groups of business and engineering students at Lakehead University, Canada. The initial studies first established market needs, and later the engineering and business feasibility of meeting the requirements for more robust, more energy efficient, more healthful housing, assuming the technical and innovation challenges would be overcome.

By early 2004, the two main researcher-inventors had committed to satisfying the need for better housing by building on the dynamic air approach. The research-inventors and collaborators agreed on these five research aims:

1. Understand and apply the physics of heat loss and gain;
2. Overcome technical and commercial approaches of the past;
3. Improve design in terms of fresh air, energy efficiency and durability;
4. Address funding for design, demonstration, and testing of prototypes; and
5. Imbed a continuous improvement approach with the system (Goldratt & Cox, 2008).

Also in 2004, about the same time as the initial review of the literature on Timusk's work was completed, it became known by the authors that Lakehead University Student Union (LUSU) was planning to construct a new, energy efficient building to store and service bicycles. The servicing was to be in a heated portion that would house a club that would advocate the benefits of cycling, and teaching others how to repair and service their bicycles.

Subsequently, funding of $10,000 (CAD) was arranged. This helped the students afford the incremental cost of introducing the new EHI technology in their new building as well as installation instrumentation for testing of the EHI technology. The students agreed to accept the new EHI technology in the heated portion of their facility shown as Figure 2, an elevation view of this first demonstration of EHI.

Figure 2: Elevation View EHI Demonstration, Lakehead University 2004-2006
Source: Chow K., Cotton C. and Deemter, M. (2010)

Construction of the heated portion of the bicycle building was with standard 2x4 (or 4x2) wood framing, clad with R10 rigid insulation and R14 rock wool-fibre insulation between the studs, giving an overall insulation value of R24 in 'static' mode, that is when the fan is off and not in dynamic mode

Although insulation was nominally rated at approximately R24 in 'static' mode, the dynamic mode makes for much higher thermal resistance because conductive heat is recovered by the air brought 'dynamically' through the exterior envelope.

UNDERSTANDING DYNAMIC AIR FAILURES OF THE 1990S

Understanding past failure and success of both engineering and management was critical to moving from overall failure to successful innovation that has resulted in the Efficient House Innovation. One reason for the disappointing energy efficiency results in Timusk's Ontario house of the early 1980s was that important technical aspects had not been taken into account or had been only partially taken into account.

For example, not enough thought was given to depressurisation, and no attention was given to both radiation of heat or drawing in fresh air and recovering heat from the largest uninterrupted area of houses: the exterior facing ceiling (and potentially the floor) areas. Such critique applied to Timusk's two experimental houses in Edmonton (Lstiburek, 2002) and also likely applied to the Swedish houses of the 1980s.

All was not lost in past failure to improve and commercialise the Dynamic Air Approach for the Edmonton Alberta demonstration project in the mid to late 1980s. It was this early work that inspired the Lakehead University research team to revive the "dynamic air" idea by extending and adding new features, and improving performance and practicality.

The Efficient House Invention (EHI)

As mentioned, in 2004, the architect and the authors worked together with Lakehead University Student Union (LUSU) to have the improved innovation demonstrated and tested in the 72.5 S.M. or approximately 780 sq. ft. structure shown as Figure 1, constructed by a local contractor and supervised by the co-author of this paper, also head of civil engineering at Lakehead University.

The demonstration was completed in 2006 with modest financial support from Lakehead University and Federal agencies, assisted by LU's Innovation Management office and the students. The basic principles of the dynamic wall or more generally dynamic envelope technology were illustrated by the formulas on pages three and four and demonstrated in the structure shown as Figure 2 on page 51.

Typical test results in the following Figure 3 indicate performance of the EHI system in each of the North, South, East and West facing walls, and exterior facing ceiling.

In winter, the relatively drier cool air is drawn though the envelope in a controlled way, though perforations in the rigid insulation and then through the fibre insulation where the air is collected and returned to the 'house', in this case the heated portion of the bicycle building. This has three major effects: fresh air is supplied, conductive heat is recovered; and the structure is keep dry and robust. When the flow of air is reversed the house can be kept cool in summer season (exactly the reverse).

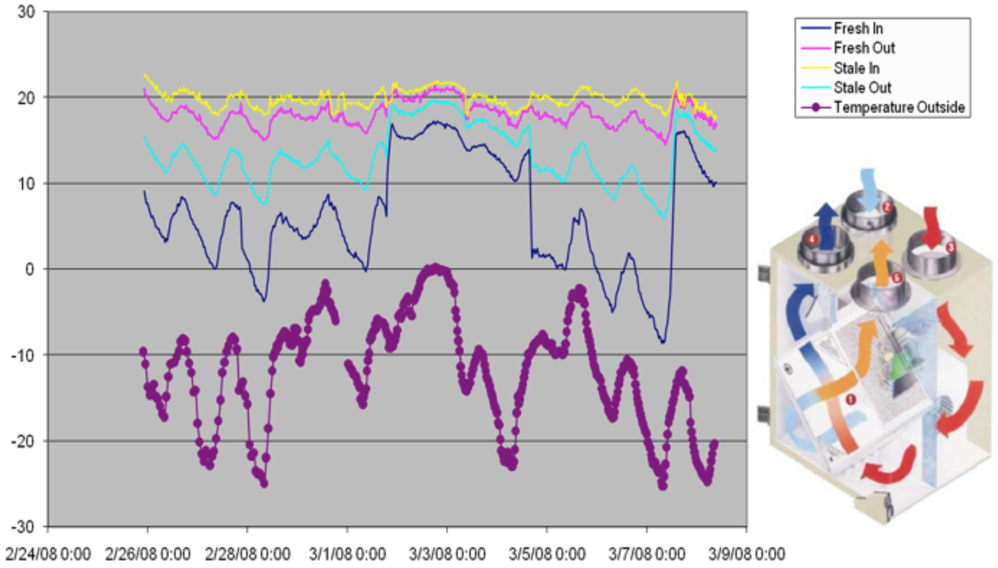

Figure 3: EHI Results Lakehead University Bicycle Building 2008 Winter Season Source: Tracz, Kapush and Mcquaker (2008),), unpublished report, Lakehead University

Adding the reflective material to the normal within-wall insulation reflect heat back (in winter) or out (summer) and boosts both the effectiveness and the efficiency of the EHI system. Initial test results over winter 2007/2008 indicated that the EHI in active mode (e.g., air drawn through the walls) was 25% to 30% more efficient than when inactive (e.g. air not drawn through the walls). However, as will be seen, these results did not answer how much more efficient is the EHI than conventional construction.

The question is, how does the Efficient House compare with buildings and houses built to the current Building Code of Canada? This critical observation and question sent the authors back to designing and testing baseline structures to building code requirements and other experimental structures, using aspects of Efficient House technology to test these against the same performance-based criteria. From 2010 to date, design and construction of two test hut prototypes was to answer the question and ready the innovation for patent applications. Figure 4 below shows an image of the two test huts each 8 ft. x 8 ft. (64 sq. ft.), one hut to Canadian Building Code and the other with EHI breathing envelope technology.

Figure 4: Comparison Test Huts – Standard Code on Left, Dynamic on Right
Source: Authors own

Progress from 2010 to 2015

It took two years from 2010 to 2012 to apply and receive the $10,000 funding, assemble materials and organise engineering students to build and monitor the test huts under supervision. Part of the delay was the engineering professor in charge of construction and monitoring going on a year of Sabbatical leave. Figure 5 shows charted results from a report on the test huts by the engineering students (Roshart et al., 2015) supervised by one author in consultation with the other author of this paper.

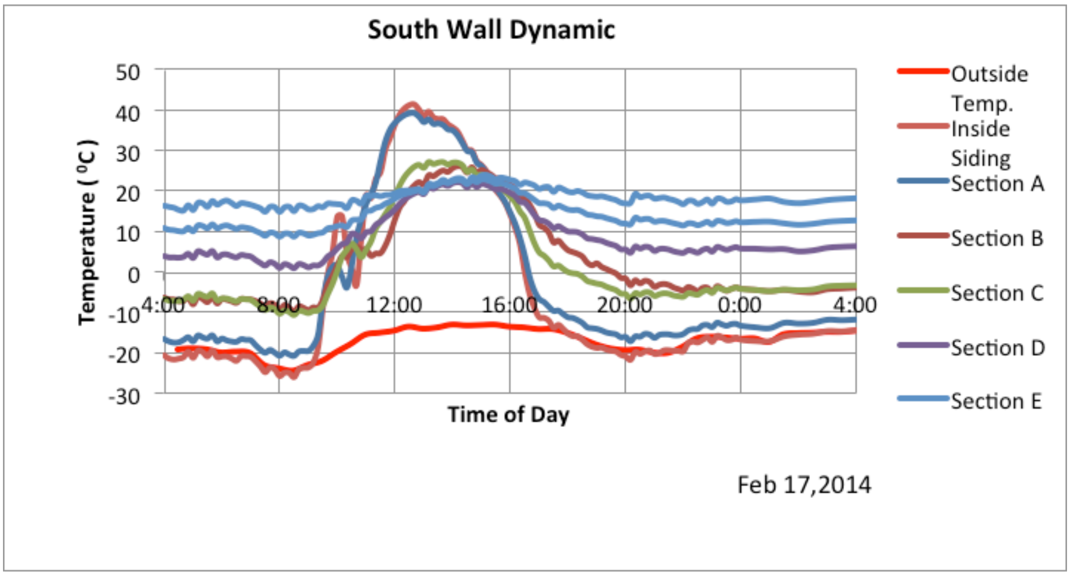

Figure 5: Daily EHI Temperatures: South Wall, Winter 2014
Source: Rosart, C., Couwenberg, P., Gilbride, C. and Jessome, J. (2015)

Daily EHI Temperatures: South Wall, Winter 2014

As the reader will see from Figure 5, temperatures in the afternoon are elevated to over 40 degrees Celsius (˚C) behind the siding on the south-facing side of the hut, when the outside air temperature is -12˚C, a difference of 52˚C. This is a source of free heat since the dynamic envelope design can draw it through the structure, collect this dry warm air and redistribute it throughout the house. Figure 6 below indicates typical winter profile temperatures through the South facing wall in Canada.

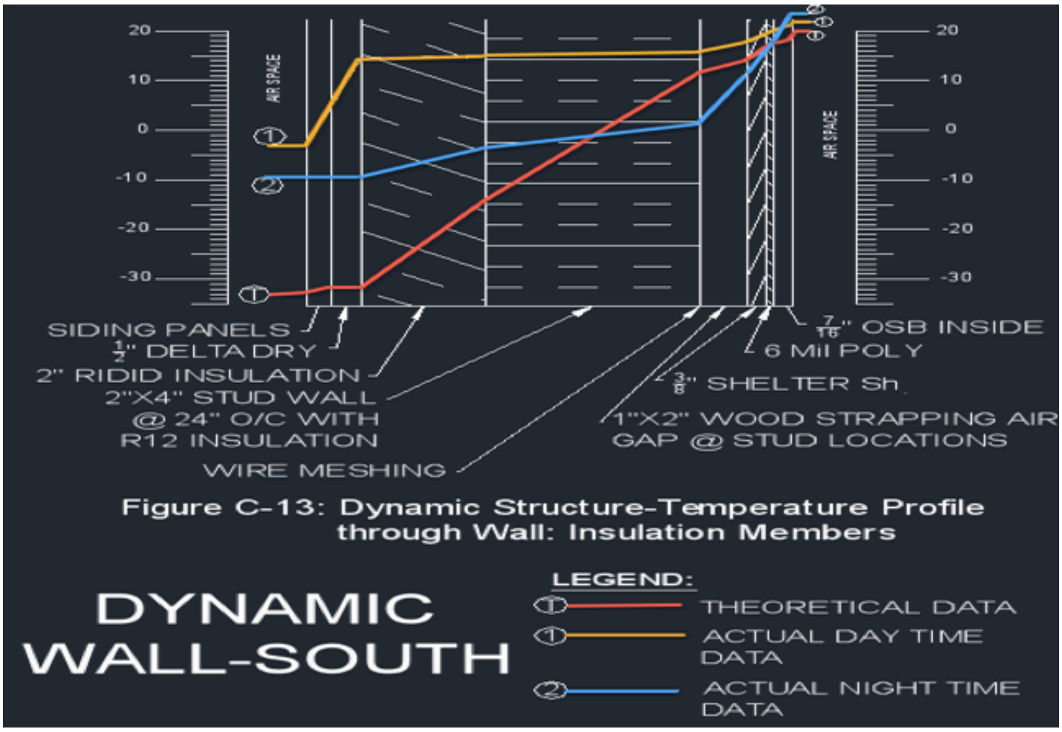

Figure 6: Temperature Profiles through the South Wall of Dynamic Structure
Source: Rosart, C., Couwenberg, P., Gilbride, C. and Jessome, J. (2015)

Line T is Thunder Bay winter design condition, inside 20˚C and outside -33˚C (note that this line would move upwards to match actual, not design temperatures). Line 1 is a sample measured daytime profile when the outside temperature was -4˚C and the inside heated space was maintained at 22˚C. The radiant heat gain behind the siding is apparent and the heat is pulled through the insulation by the dynamic air flow as evidenced by the raised profile slope. Line 2 is a sample nighttime profile. There is no longer any radiant heat increment behind the siding and the colder air is pulled through the wall causing the ‘sag’ in the through section temperature profile. The pattern clearly demonstrates that a dynamic flow exists. A study of these measured profiles with varying fan speeds will enable the optimum air flow to be determined.

In short, the first prototype and test huts together establish Proof of Concept, and a Canadian Patent for the EHI was granted in February 2014. This achievement has been with support and effort by the authors and students and many others. Today, the control is manual. In the future the system needs to be automatically controlled to optimise internal conditions such as faced by buildings in the North, likely including all of Canada, and in the South, for example in at least some parts of New Zealand.

Subsequent testing, conducted between after 2010, indicated efficiency gain between conventional construction and EHI is approximately 30% to 50%, and air quality can be achieved without a separate air-to-air heat exchanger. In other words, the heat required to heat an EHI building could be about 40% that of a building built to current Canadian Building Code with nominal R24 insulation (note the EHI challenges these nominal ratings). Modest extra incremental cost of the EHI would be due to the control system and some extra level of care in the design and construction of the building, not in the amount of materials which actually is less.

In summary, efficiency increases are important and so too are extra durability of structure and health considerations as the EHI delivers fresh air in just the right amount without the necessity of failure-prone air-to-air heat exchangers. All this, and the EHI is a low energy building technique that can be complemented by efficient technologies, such as efficient furnaces, and solar, wind and geotechnical power.

ACCOMPLISHMENT OF RESEARCH AND DEVELOPMENT AIMS

The EHI did accomplish the research aims in general terms as it promises to revolutionise housing in the North and in the South, single and two-level houses or light frame buildings. It is a total system that conserves more energy, provides healthful fresh air to occupants more reliably and provides superior durability of the exterior shell. This system approach is first to take into account and optimally reverse and/or mitigate all three major mechanisms of heat loss and gain through the exterior shell or envelope of the building.

Implications for the EHI, Going Forward

Implications relate to the insights that have been gained by attempting to innovate in a tertiary education setting that is open to industry without being controlled by industry. These implications are expressed in terms of general responses to the five research questions posed. Both engineering technology and management of the innovation process must be jointly considered with innovation, and this applies to the EHI. Feasibility of the Efficient House is nearing completion. It needs more work and resources to be fully developed and commercialised.

From the beginning the idea was to establish a Centre for research, education and training for Housing in the North at Lakehead University, to permanently secure resources to further develop and eventually commercialise the EHI, and to continually improve and develop Efficient House technology more optimally.

CONCLUSIONS

The Efficient House Innovation (EHI) illustrates how important it is for the right people to work together with the right supports, and at the right time. Also Centres for Housing Innovation need be established in both the North and South to attract the right resources and the right people and keep them together on a long term basis. Here housing innovation would be a need-based process of adaptation and improvement for the particular circumstances of regions both North and South.

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